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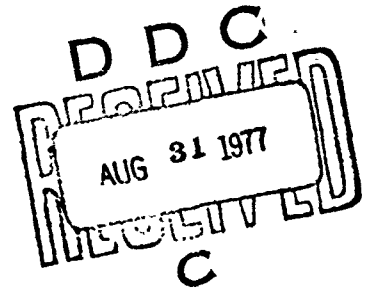
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NOMOGRAPHY FOR OPERATIONS RESEARCH

Russell C. Coile

Professional Paper No. 187

April 1977

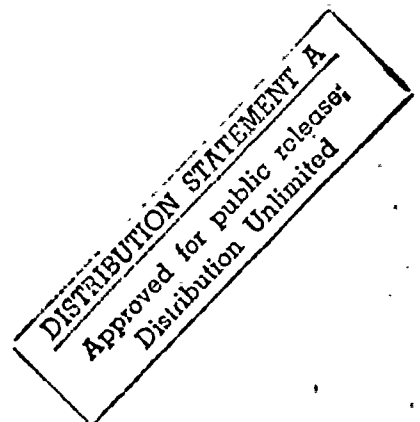


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6 NOMOGRAPHY FOR OPERATIONS RESEARCH,

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Center for Naval Analyses
University of Rochester

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NOMOGRAPHY FOR OPERATIONS RESEARCH

ABSTRACT

△ Nomographs have been found to be useful in operations research. These charts for graphical computation have the advantages to the user of being non-electronic, quick, and easy to use. They can be designed to present complicated mathematical formulas in a simple format to non-mathematical people. Disadvantages are the slide-rule type accuracy and the possible lack of *feel* that families of curves might possibly give.

Research on applications of nomographs in solving operations research problems has lead to development of some procedures for simplified design of nomographs. Examples of nomographs for acoustical design, radar, and sonar illustrate these procedures. *8*

Figure
1

NOMOGRAPHY FOR OPERATIONS RESEARCH

Russell C. Coile

Center for Naval Analyses

INTRODUCTION

Nomographs are charts for graphical calculations. Nomography
Figure 2 was invented by a French engineer, Maurice d'Ocagne, in 1884. He coined the word "nomography" from the Greek nomos, law, and the Greek graphos, drawn or written, to describe these graphical representations of mathematical laws. Nomographs are also called nomograms or alignment charts.

Nomographs have a number of advantages over other methods of
Figure 3 computation in some operations research situations. They are non-electronic, quick and easy to use. They do not require interpolation. The designer of the nomograph can pre-digest the mathematics and make the graphical computation palatable for non-mathematical people. Also, some problems permit a translation of variables into more familiar terms. The disadvantages of nomographs are the lack of accuracy and the lack of "feel" that some graphical displays of curves might give.

The approach I will use this morning is to show you how easy
Figure 4 it is to construct nomographs for operations research applications. First we will examine the classification of equations into the types that are appropriate for nomography. Then we will use a worksheet for planning the scale equations and scale spacing. Finally,

we will use plotting charts to mark the scales. Then I will show you some examples of nomography. As a matter of fact, may I show you one example right now? Suppose you were concerned with doppler shift in underwater acoustics as a function of relative velocity and sonar frequency. The nomograph for Doppler Shift has three scales; Δf , doppler shift in Hertz, v , relative velocity in knots, and f sonar frequency in kiloHertz. The nomograph is a graphical representation of the formula

Figure
5

$$\Delta f = \frac{2v}{c} f$$

where c is the velocity of sound.

To use the nomograph, one can lay a straight-edge between 5 knots on the relative velocity scale and 20 kiloHertz on the sonar frequency scale and read the answer of 70 Hertz on the Δf doppler shift scale.

CONSTRUCTION OF NOMOGRAPHS

The first step in nomography is examination of the mathematical formula. Nomographs can usually be constructed for equations of three variables which are or can be manipulated into the form called Type I below.

Type I equations.

Figure
6

$$f_1(x) + f_2(y) = f_3(z)$$

Nomographs can similarly be constructed for equations of four or more variables of the Type II form.

Type II equations,

Figure
7

$$f_1(x) + f_2(y) + f_3(z) = f_4(r)$$

Figures
8&9

To construct a nomogram we must work out the plotting equation for each line after we have decided on the general approach and the spacing between lines. A nomograph Work Sheet helps organize these calculations. An example has been worked out for a military problem of estimating the possible radius of an enemy submarine's escape circle after loss of contact by an anti-submarine ship. In this example,

Figures
10&11

$$vt = r$$

where

v submarine speed in knots

t elapsed time in hours

r radius of sub escape circle in nautical miles

Some nomographic plotting charts developed at M.I.T.'s Mathematical Laboratory in 1918 by Professor Joseph Lipka (Reference 1) will be found to be useful in marking the scales. Both uniform and logarithmic scales can be easily marked using these MIT charts.

NOMOGRAPHIC ACCURACY

Nomographs have slide-rule type accuracy. Nomographs constructed in the original French style originated by d'Ocagne have poorer accuracy as the number of variables increases. However, Professor Brodetsky (Reference 2) of Leeds University in England

Figures

14-22

developed a method for preserving accuracy no matter how many variables are involved. For example, a nomograph for the multiplication of (X) and (Y) in the French style results in the product answer (XY) on the inside being at half-scale. The English method would put the answer on the outside at full scale. Similarly, the multiplication of (X), (Y) and (Z) in the French style ends up with the (XY)Z answer on the inside at one-quarter scale. The English method preserves full scale accuracy for the answer on the outside. Division is handled in a similar fashion.

An example of seven variables illustrates how powerful this English method is. Professor Brodetsky also suggested starting with the evaluation of the denominator first in the sequence of calculations. Hence in the design of a nomograph for

Figure

23

$$A = \frac{XYZ}{PQR}$$

what we actually do is consider this to be

$$A = \left(\left[\frac{X}{(PQ)R} \right] Y \right) Z$$

and begin with $P \times Q$, then $(PQ) \times R$, etc.

LOGARITHMIC VS LINEAR SCALES

Some nomographs may be easier to use if made with linear rather than logarithmic scales. The nomograph for

Figures

24&25

$$Z = \frac{YQ}{X}$$

can be designed for either logarithmic or linear scales as illustrated.

EXAMPLES

A nomograph which could be used in search and rescue operations for planning the number of aircraft required to search an ocean area for an aircraft forced down at sea is based on the following expression given by Morse and Kimball (Reference 3)

Figure
26

$$p = 1 - e^{-\left(\frac{WLN}{A}\right)}$$

where

p the percent chance of detection

W sweep width in miles

L length of search track

N number of search aircraft

A area to be searched in square miles

The target strength of fish as a function of size (length, actually) and sonar frequency is based on the following expressions developed by Love (Reference 4)

Figure
27

$$T_D = 19.1 \log L + 0.9 \log \lambda - 34.2$$

$$T_S = 22.8 \log L - 2.8 \log \lambda - 32.4$$

where

T_D target strength in dB for dorsal aspect

T_S target strength for side aspect

L length of fish in feet,

λ wavelength of sound in feet.

Figure
28

A BAR-O-GRAPH nomograph of blood-alcohol concentration in percent has been designed to assist in determining when enough is enough. Various states have different levels of blood-alcohol concentration for legal definitions of intoxication. I believe the official BAC level in California is 0.1%. If you weigh 140 pounds or fewer, it would not appear to be prudent (or legal) to drink more than two Manhattans within an hour at the ORSA mixer tonight if you plan to drive shortly thereafter.

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4. Love, Richard H. "Maximum Side-Aspect Target Strength of an Individual Fish" Journal of the Acoustical Society of America, Vol. 46, No. 3 (Part 2) pages 746-752, 1969

NOMOGRAPHY
FOR
OPERATIONS RESEARCH

BY
RUSSELL C. COILE

FIGURE 1

"NOMOGRAPH"

GREEK	<u>NOMOS</u>	LAW
GREEK	<u>GRAPHOS</u>	DRAWN OR WRITTEN

GRAPHICAL REPRESENTATION
OF A MATHEMATICAL LAW

ALSO CALLED
"NOMOGRAM"

FIGURE 2

NOMOGRAPHS

ADVANTAGES TO CONSUMER

- No Electronics
- Quick
- Easy to Use
- No Interpolation
- Predigested Math
- Translated Variables

DISADVANTAGES

- Accuracy
- No "Feel"

FIGURE 3

APPROACH

CLASSIFICATION OF EQUATIONS

WORKSHEET

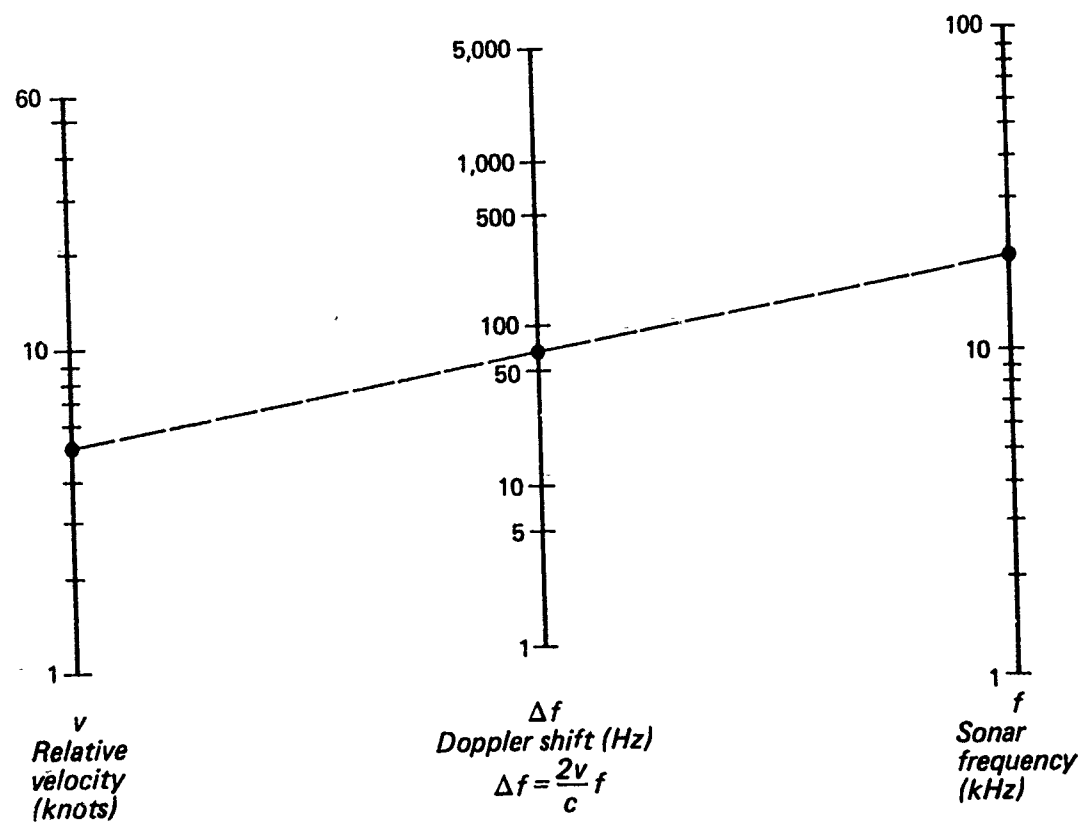
Scale Equations

Scale Spacing

PLOTTING CHARTS

EXAMPLES

FIGURE 4



PRINCIPLES OF UNDERWATER SOUND
 R.J. Urick, McGraw Hill, 1975, Page 294.

FIG. 5: DOPPLER SHIFT

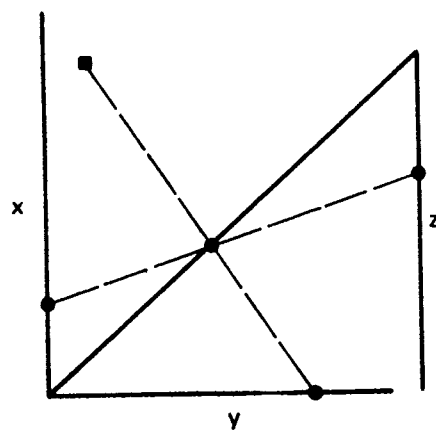
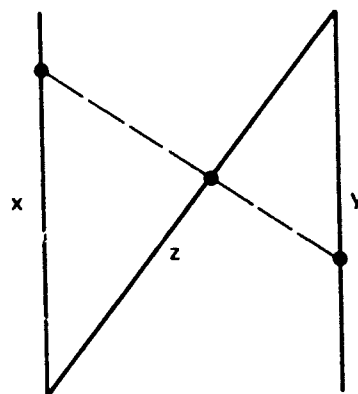
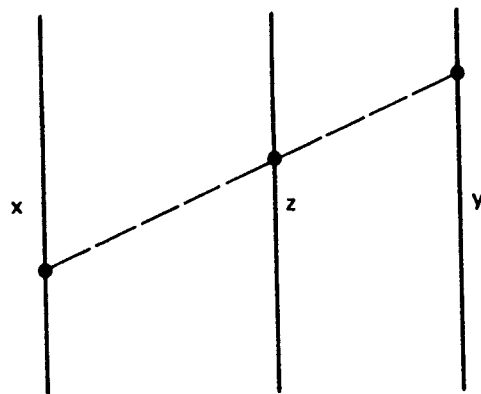


FIG. 6: TYPES OF EQUATIONS
I. $f_1(x) + f_2(y) = f_3(z)$

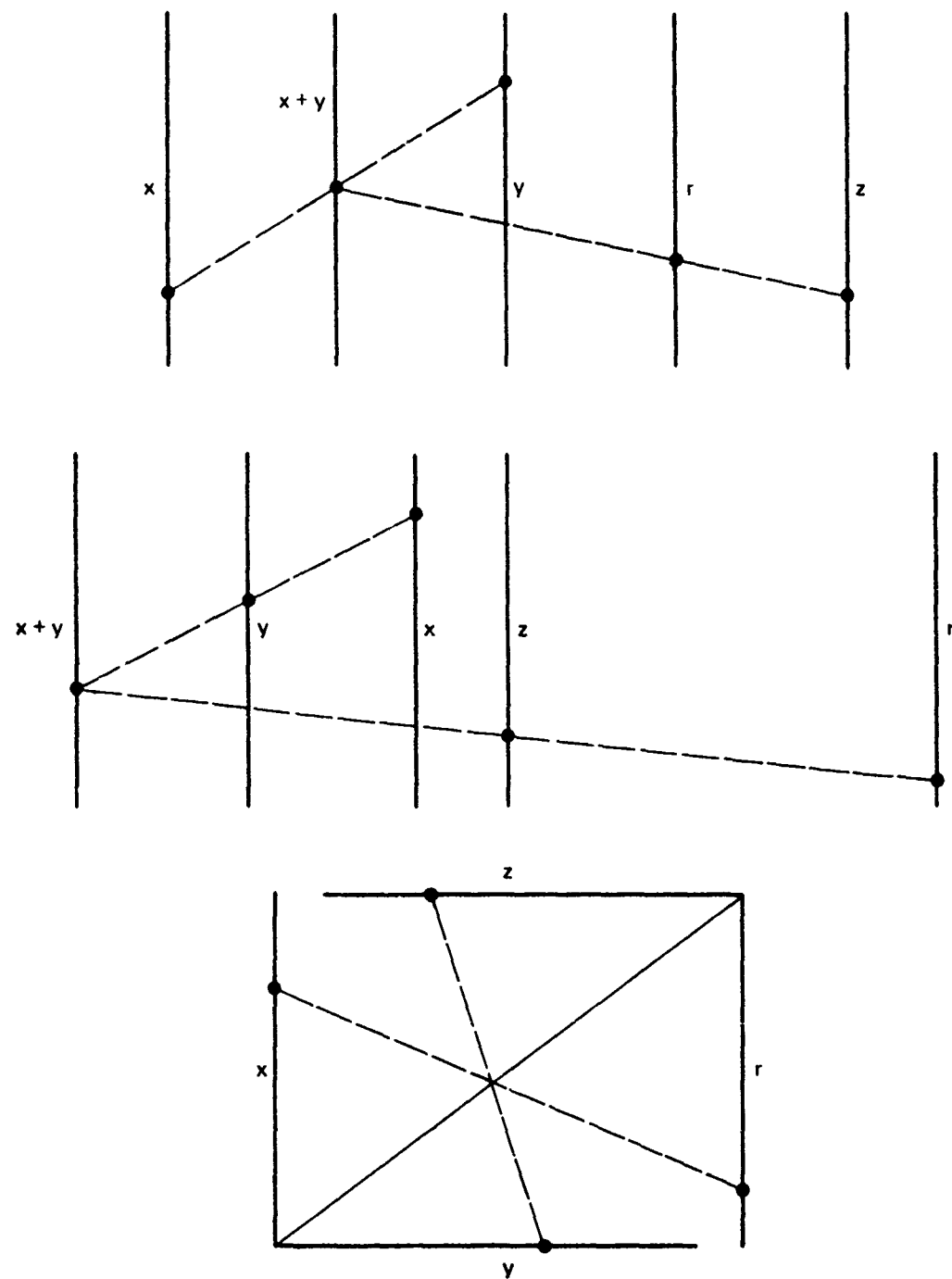


FIG. 7: TYPES OF EQUATIONS
 II. $f_1(x) + f_2(y) + f_3(z) = f_4(r)$

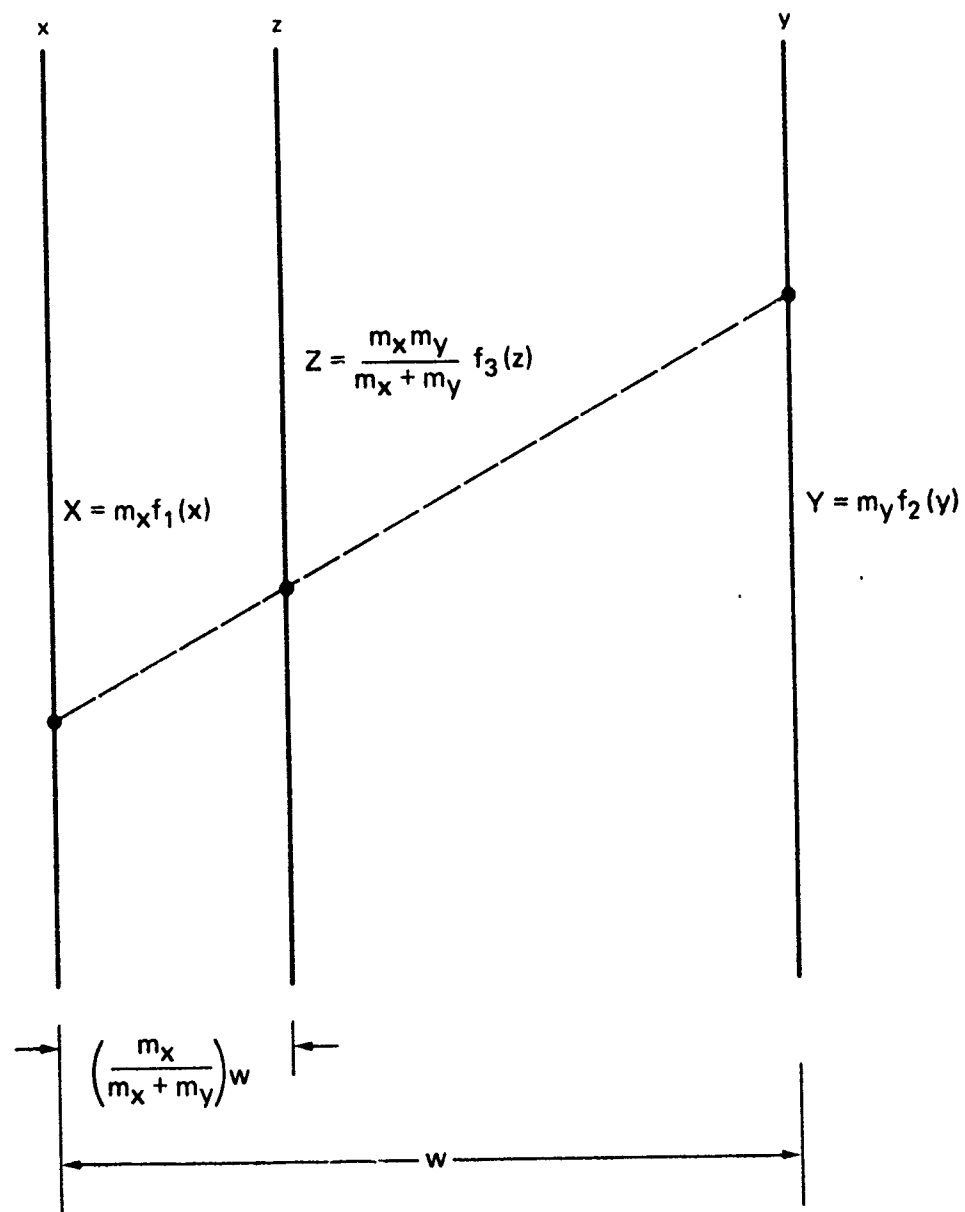


FIG. 8: TYPES OF EQUATIONS
I. $f_1(x) + f_2(y) = f_3(z)$

NOMOGRAPH WORK SHEET

NOMOGRAPH WORK SHEET

Step					
I	Identify the type of the equation.				
II	Scale X	Range	Trial factor length/range	Scale Factor m_x	Plotting Equation X
III	Scale Y	Range	Trial factor length/range	Scale Factor m_z	Plotting Equation Y
IV	Scale Z	Scale factor $m_z = \frac{m_x m_y}{m_x + m_y}$		m_z	Z
V	Z spacing from X = $\left(\frac{m_x}{m_x + m_y} \right) w$				
VI	Z starting points				
VII	Draw X scale				
VIII	Draw Y scale				
IX	Draw Z scale				
X	Check the Nomograph		Nomograph		
XI	Complete the Nomograph 1. Title 2. Equation 3. Scales labeled with symbols and units 4. Sample index line				

FIGURE 9

NOMOGRAPH WORK SHEET

Step						
I	Identify the type of the equation. $v \cdot t = r$ $f_1(x) + f_2(y) = f_3(z)$ <i>is</i> type I $\log v + \log t = \log r$					
II	Scale $x = m_x \log v$	Range $\log 25 = 1.4$ $-\log 1 = \frac{0}{1.4}$	Trial factor length/range $\frac{6}{1.4} = 4.3$	Scale Factor m_x 4	Plotting Equation $x = 4 \log v$	
III	Scale $y = m_y \log t$	Range $\log 25 = 1.4$ $-\log 1 = \frac{0}{1.4}$	Trial factor length/range $\frac{6}{1.4} = 4.3$	Scale Factor m_z 4	Plotting Equation $y = 4 \log t$	
IV	Scale $z = m_z \log r$	Scale factor $m_z = \frac{m_x m_y}{m_x + m_y} = \frac{4(4)}{4+4} = 2$			m_z 2	$z = 2 \log r$
V	Z spacing from X = $\left(\frac{m_x}{m_x + m_y} \right) w = \left(\frac{4}{4+4} \right) 4 = 2$ INCHES					
VI	Z starting points $v \cdot t = r$	$1(10) = 10$ $25(2) = 50$ $5(10) = 50$				
VII	Draw X scale OF v IN KNOTS					
VIII	Draw Y scale OF t IN HOURS					
IX	Draw Z scale OF r IN MILES					
X	Check the Nomograph $v \cdot t = r$ $5(20) = 100$		Nomograph 100			
XI	Complete the Nomograph 1. Title 3. Scales labeled with symbols and units 2. Equation 4. Sample index line					

FIGURE 10

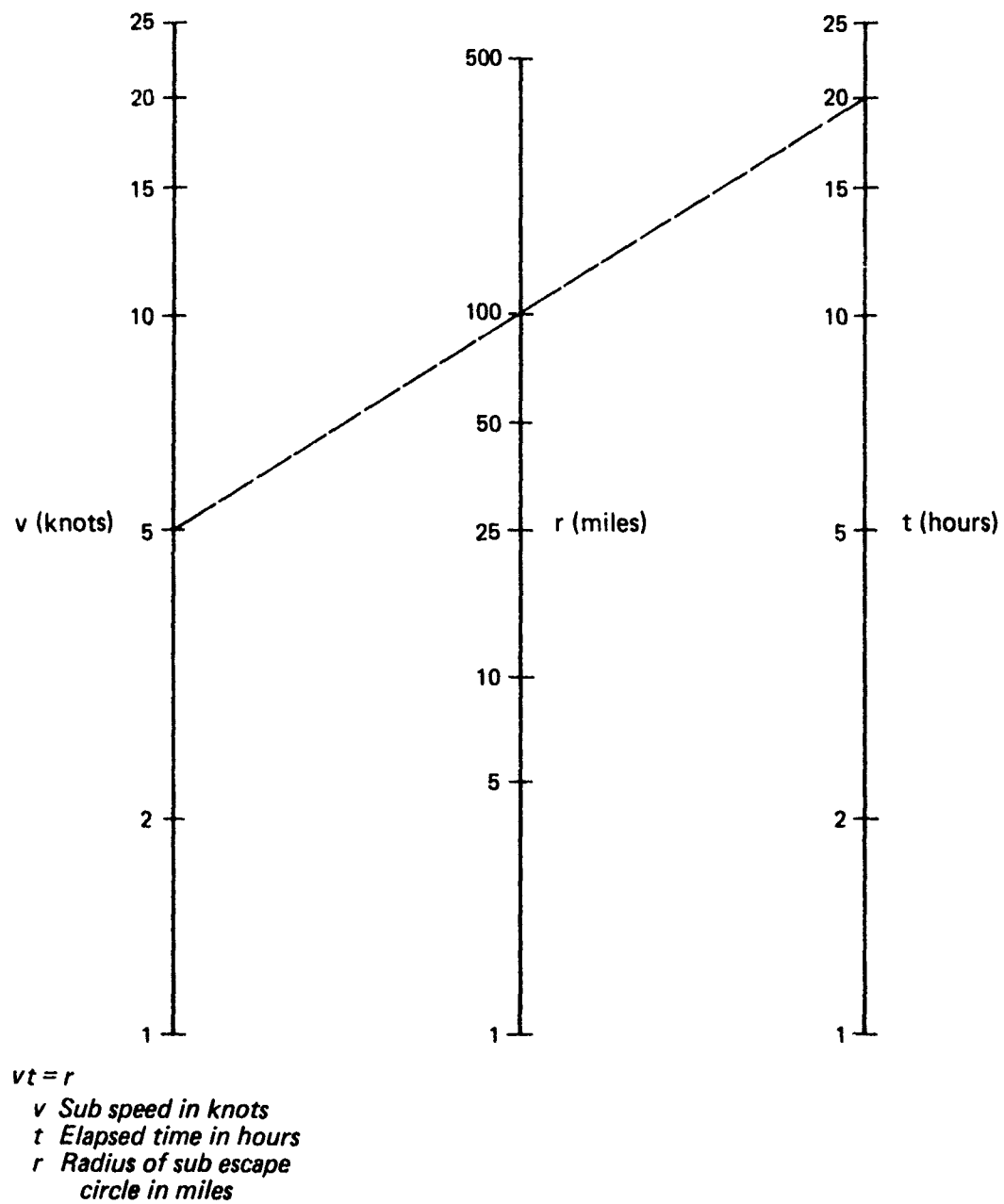


FIG. 11: RADIUS OF SUBMARINE ESCAPE CIRCLE
 AFTER LOSS OF ASW CONTACT

Scale factor "modulus" m

$$X = m_X f_1(x)$$

$$m_X = \frac{X}{f_1(x_1) - f_1(x_2)}$$

Suppose range is 5 and it is desired to fit the scale into a length of 4 inches

$$m_X = \frac{4}{5} = 0.8$$

Use the plotting chart at $m = 0.8$

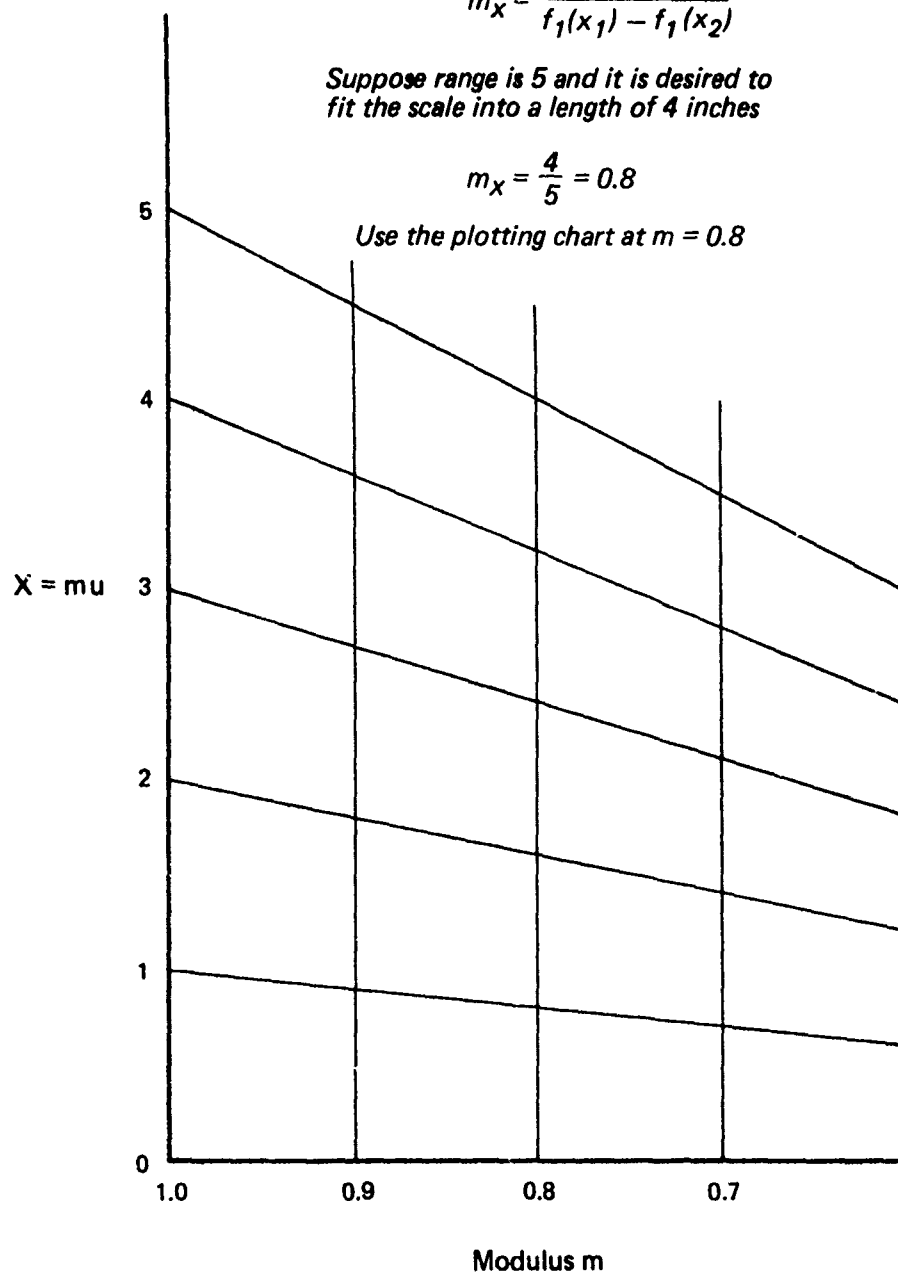


FIG. 12: SCALES FOR NOMOGRAPHS

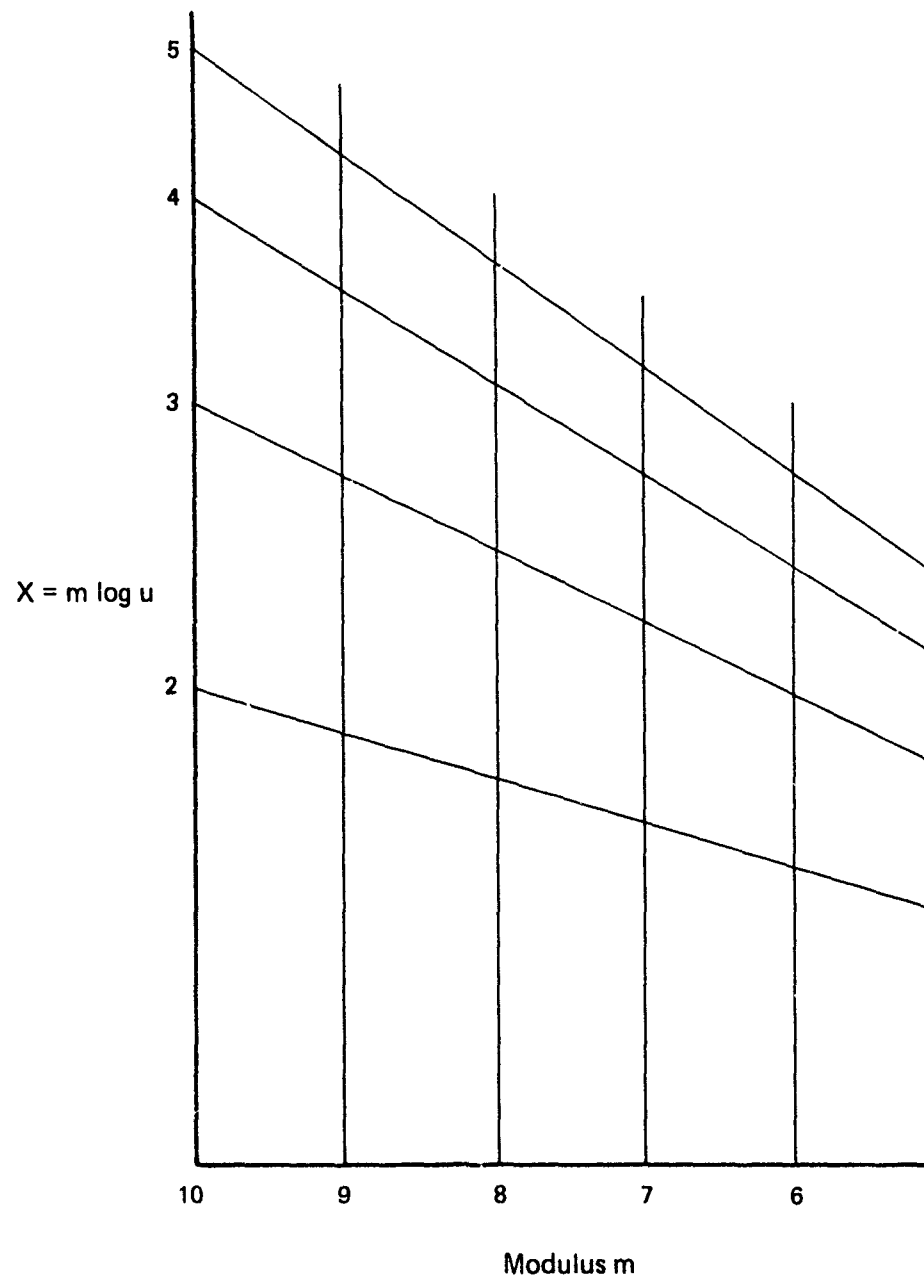


FIG. 13: LOGARITHMIC SCALES

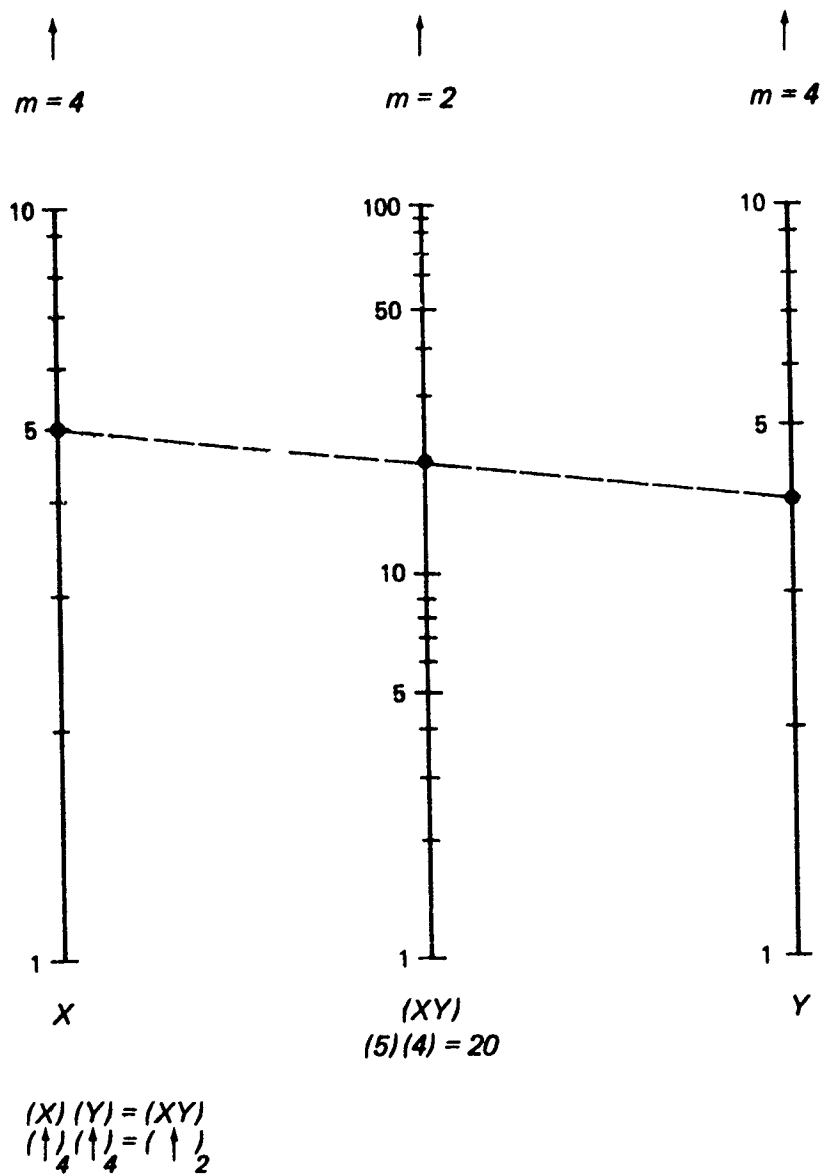


FIG. 14: MULTIPLICATION (ANSWER: INSIDE)

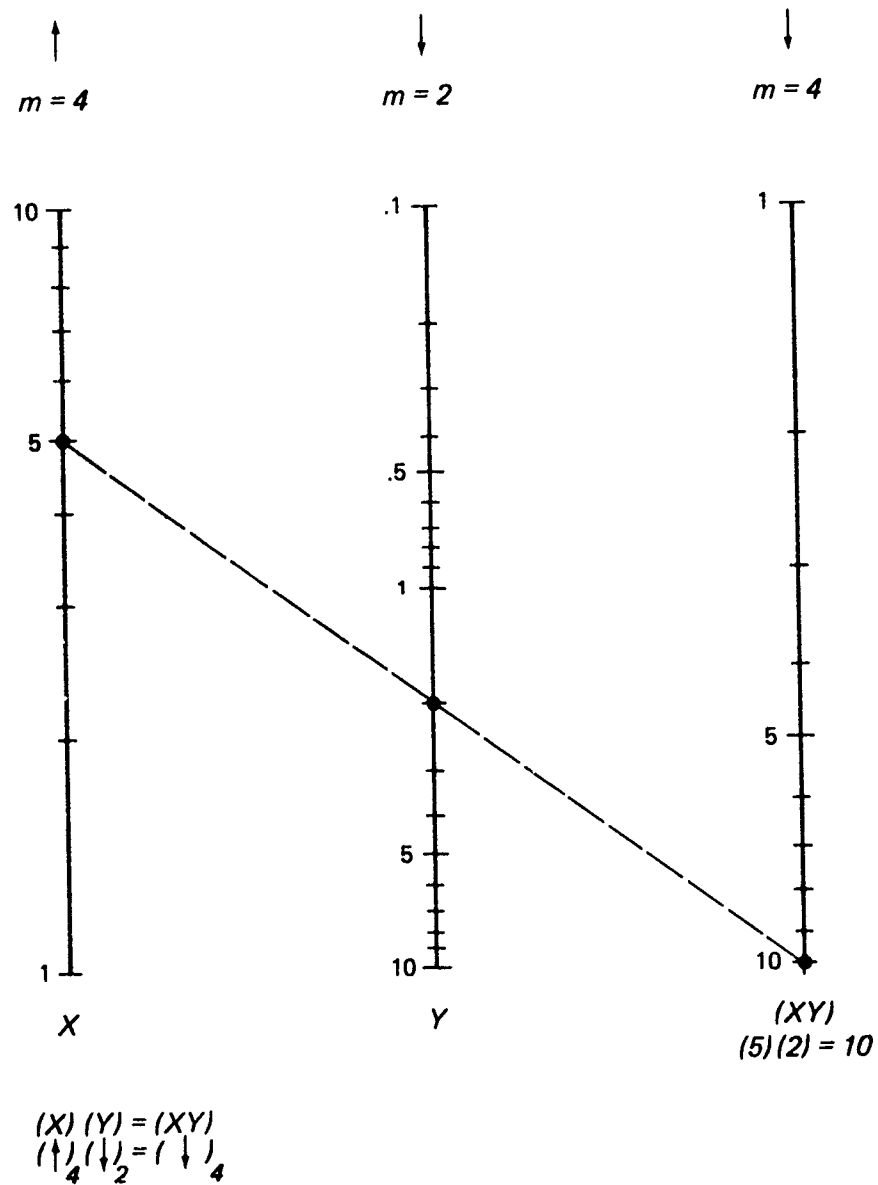


FIG. 15: MULTIPLICATION (ANSWER:OUTSIDE)

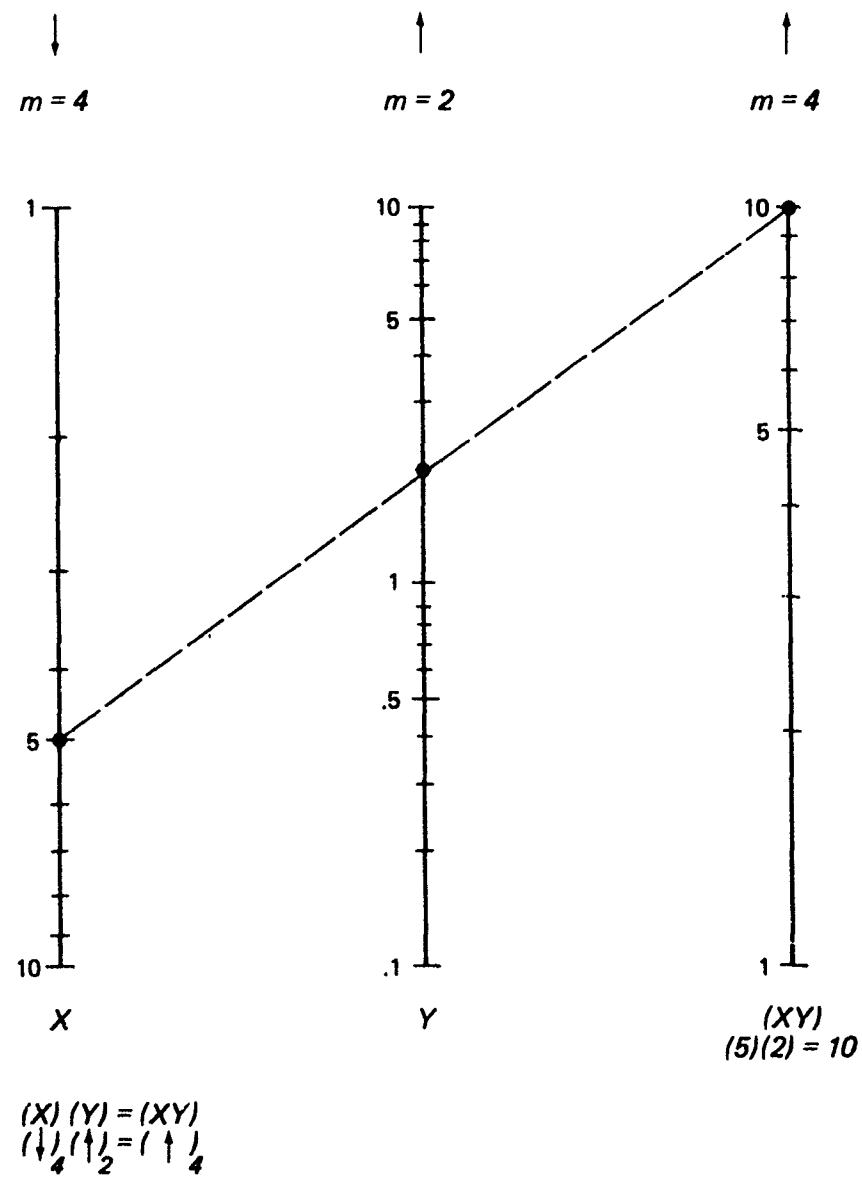


FIG. 16: MULTIPLICATION (ANSWER:OUTSIDE)

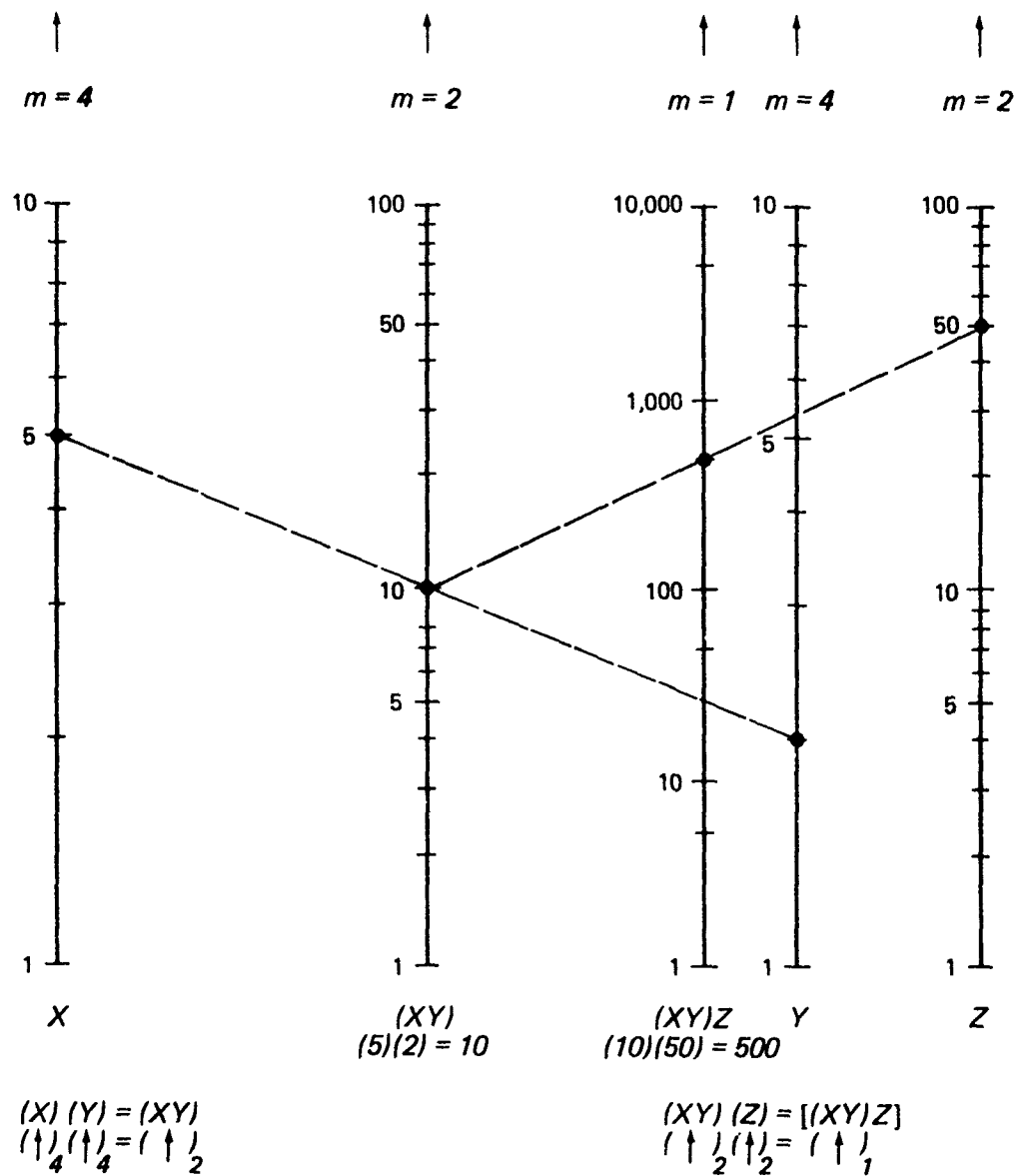


FIG. 17: MULTIPLICATION (ANSWER: INSIDE)

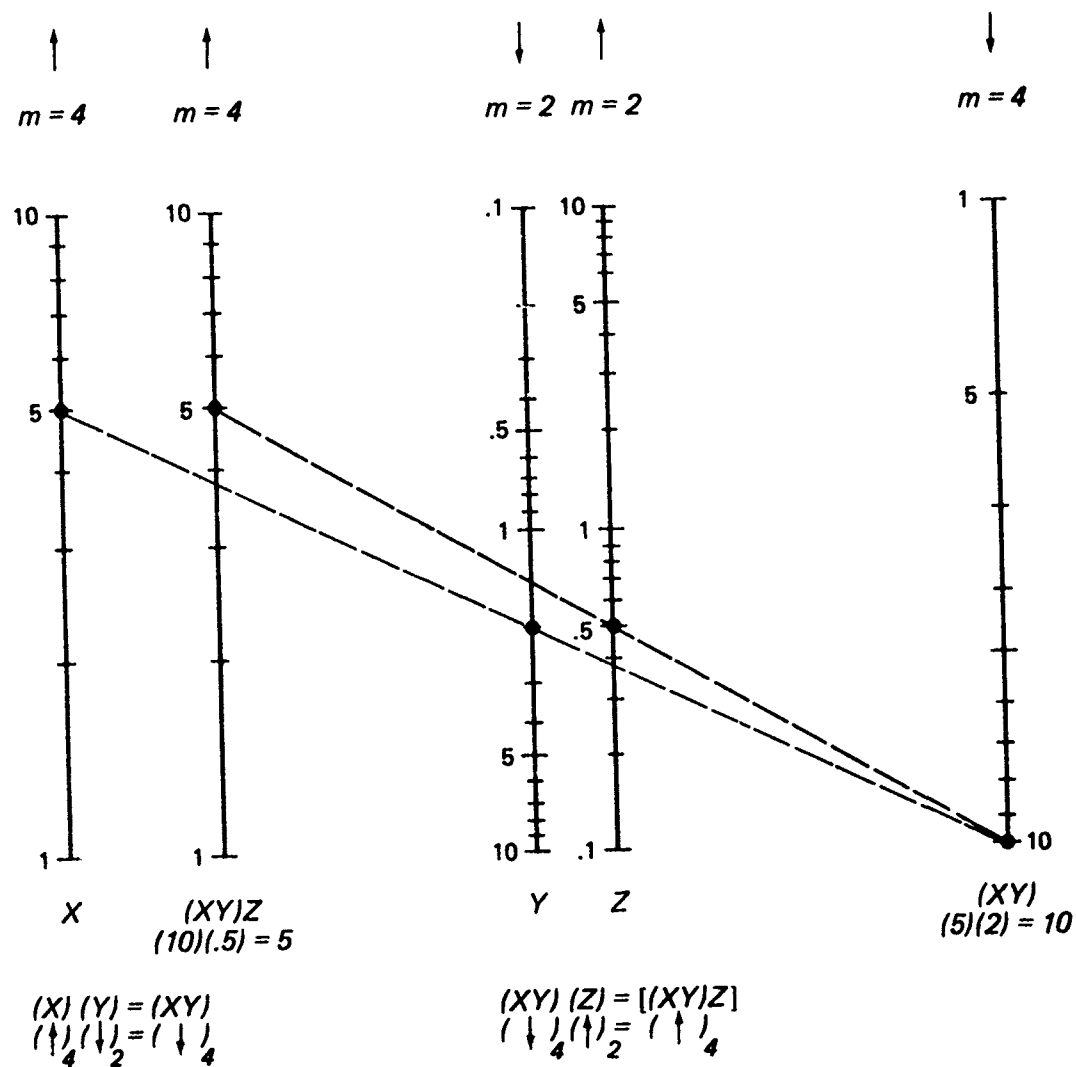


FIG. 18: MULTIPLICATION (ANSWER: OUTSIDE)

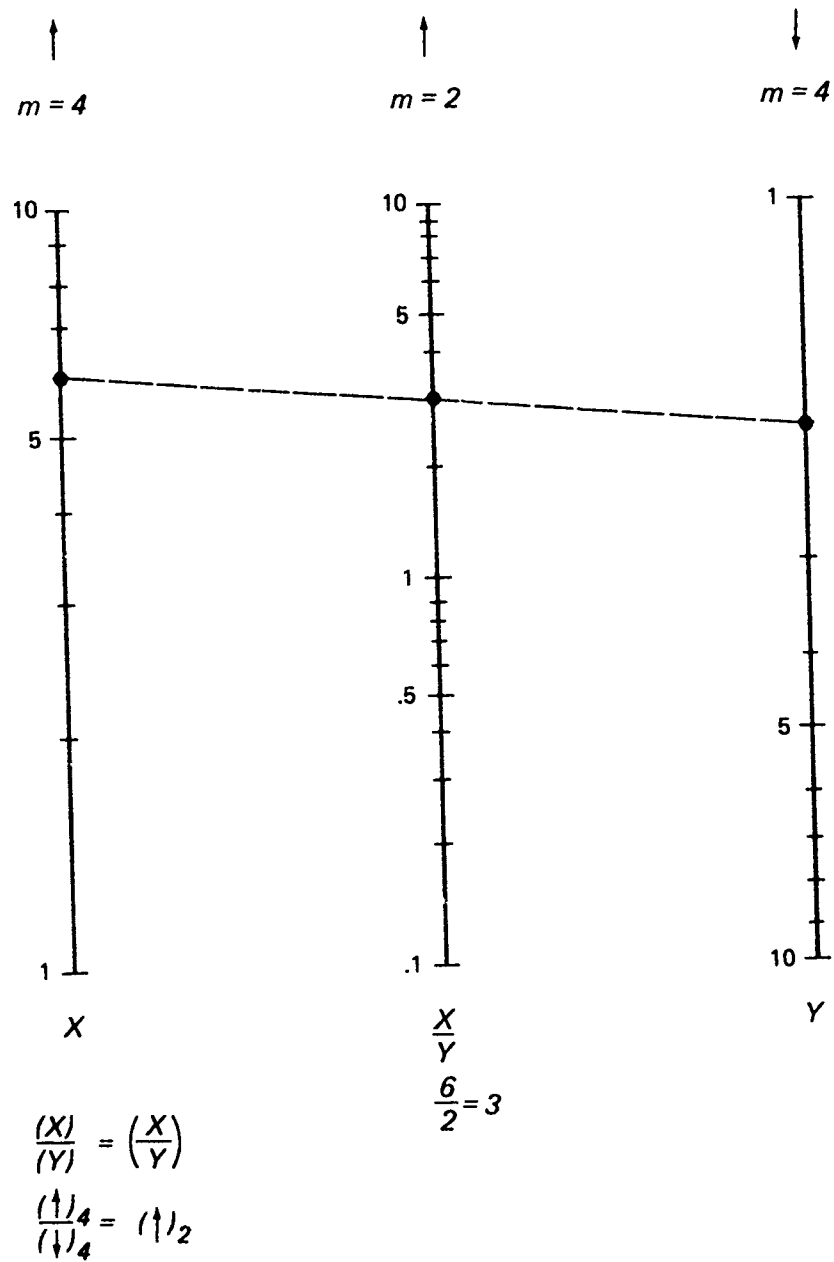


FIG. 19: DIVISION (ANSWER: INSIDE)

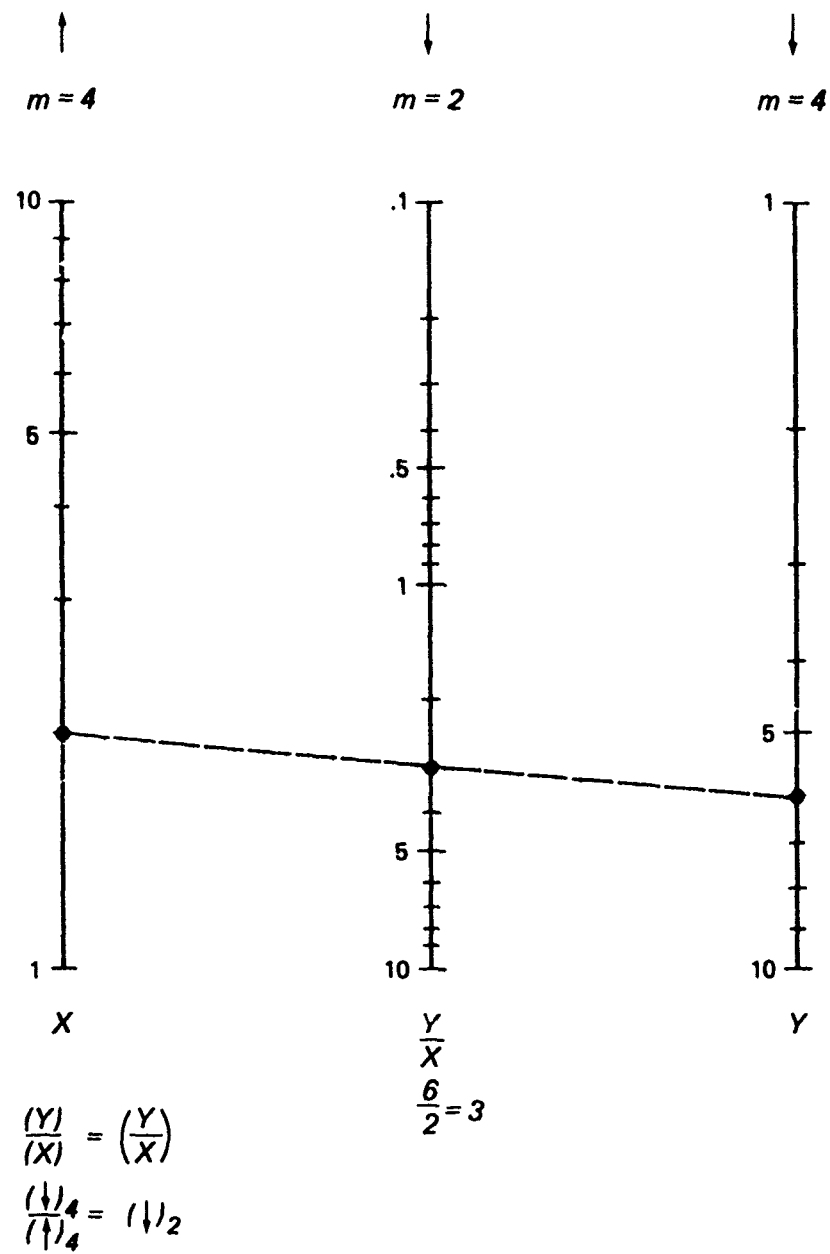


FIG. 20: DIVISION (ANSWER: INSIDE)

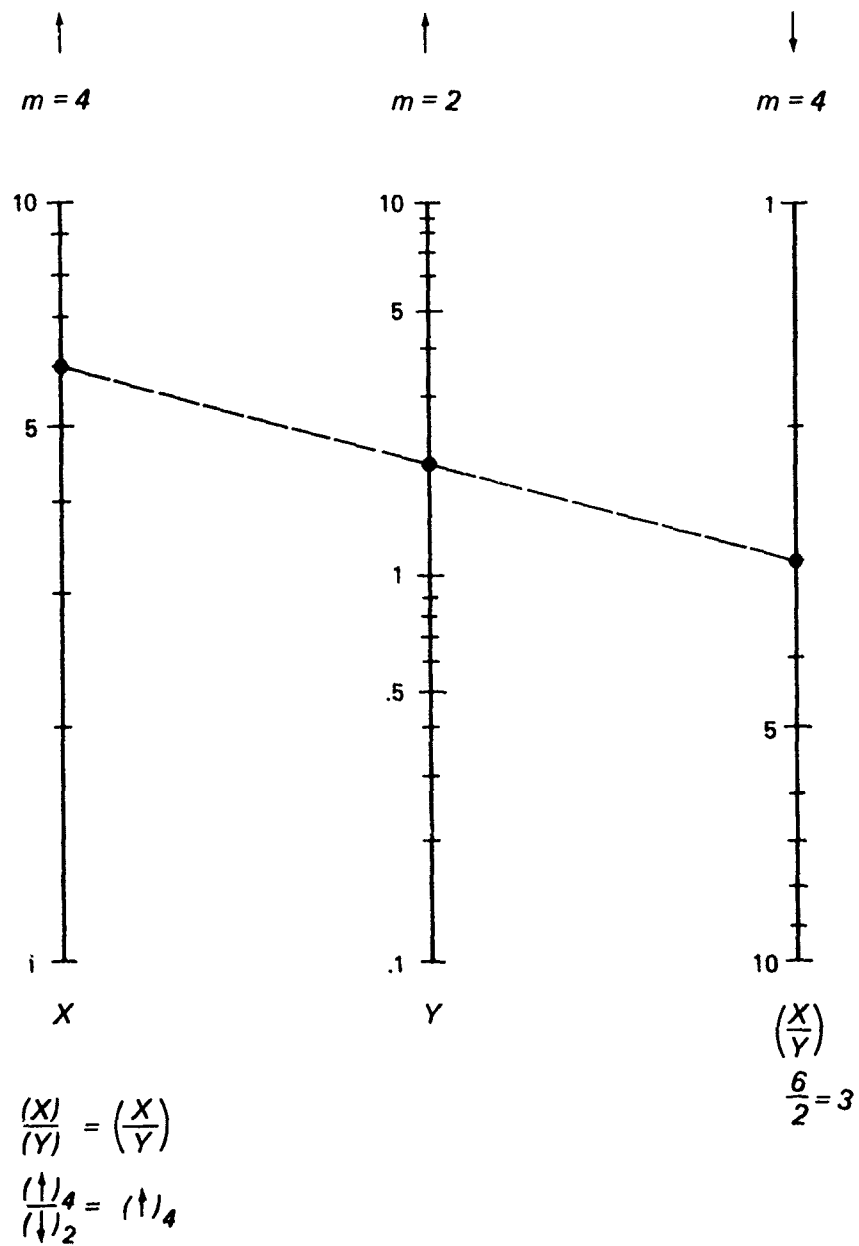


FIG. 21: DIVISION (ANSWER: OUTSIDE)

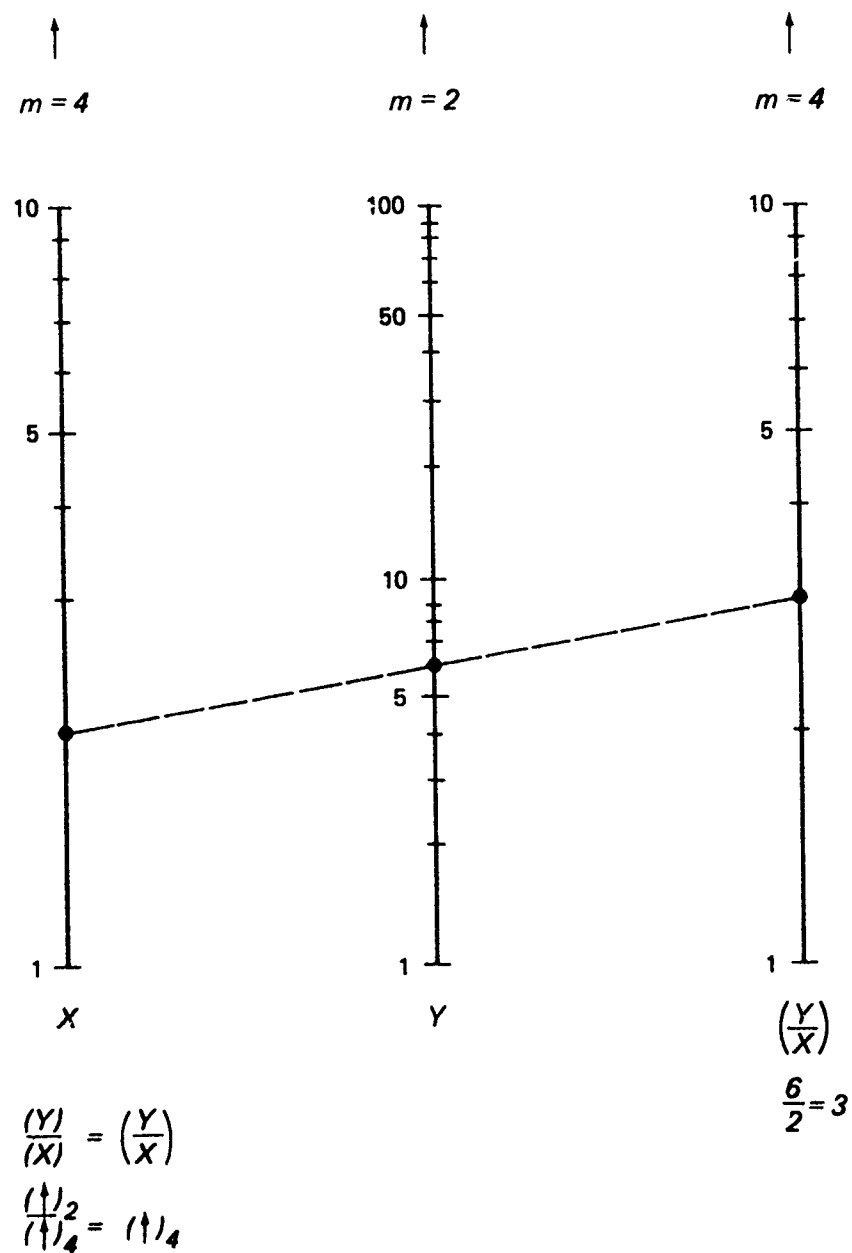
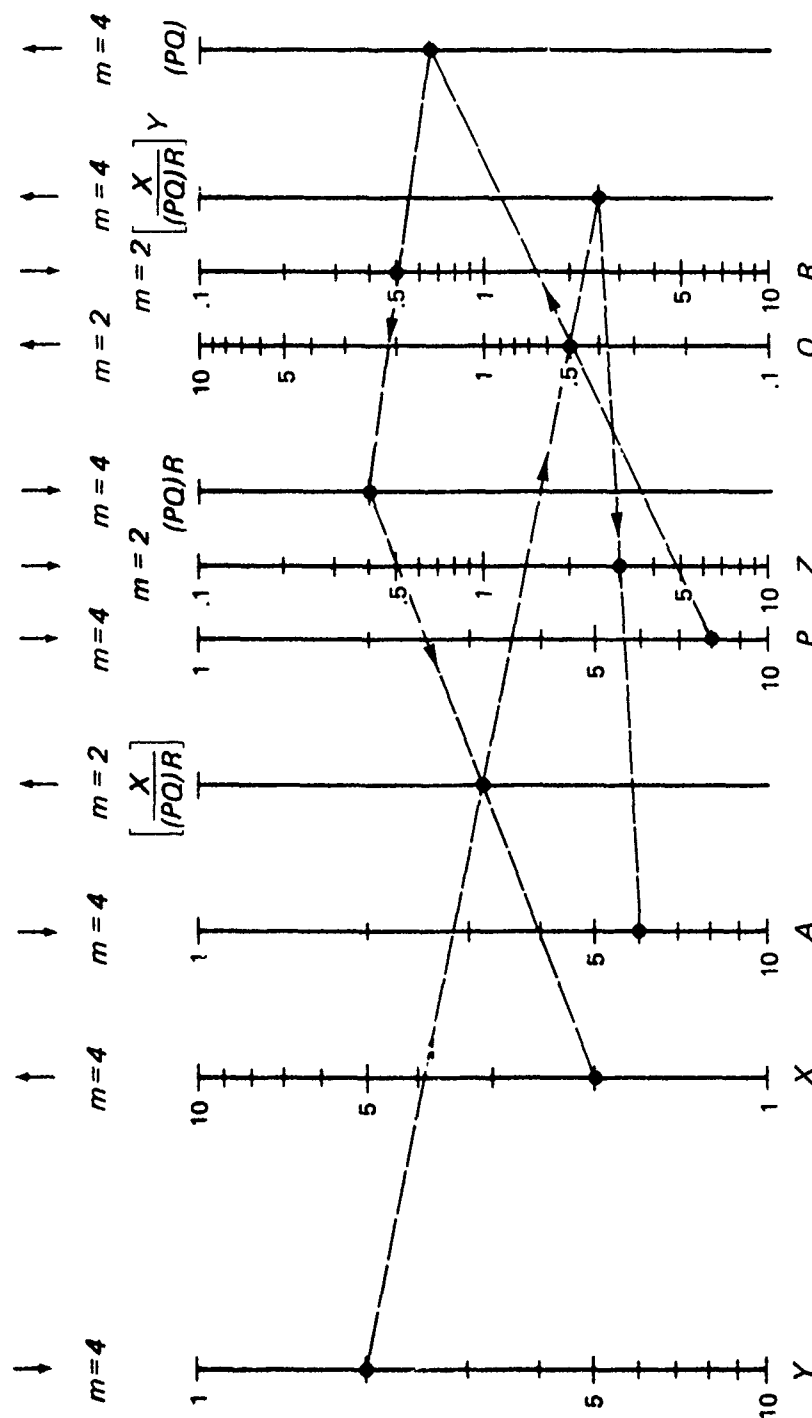
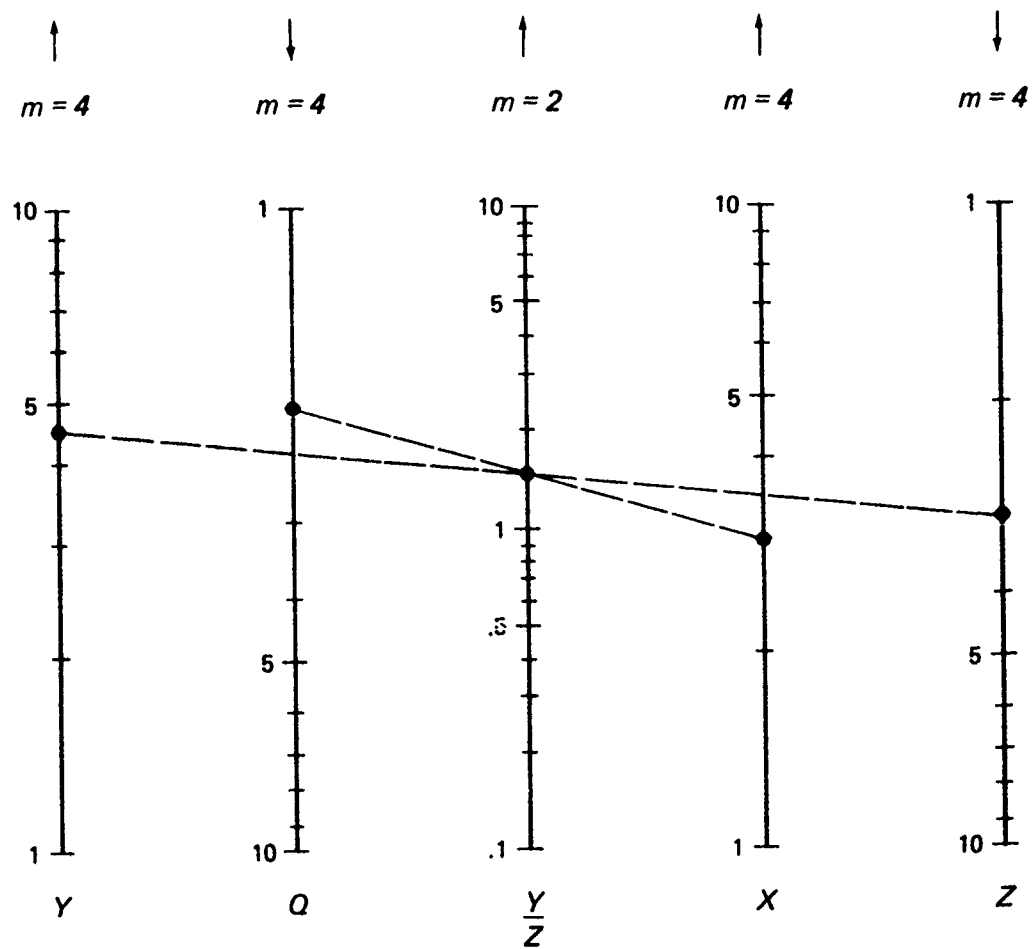


FIG. 22: DIVISION (ANSWER:OUTSIDE)



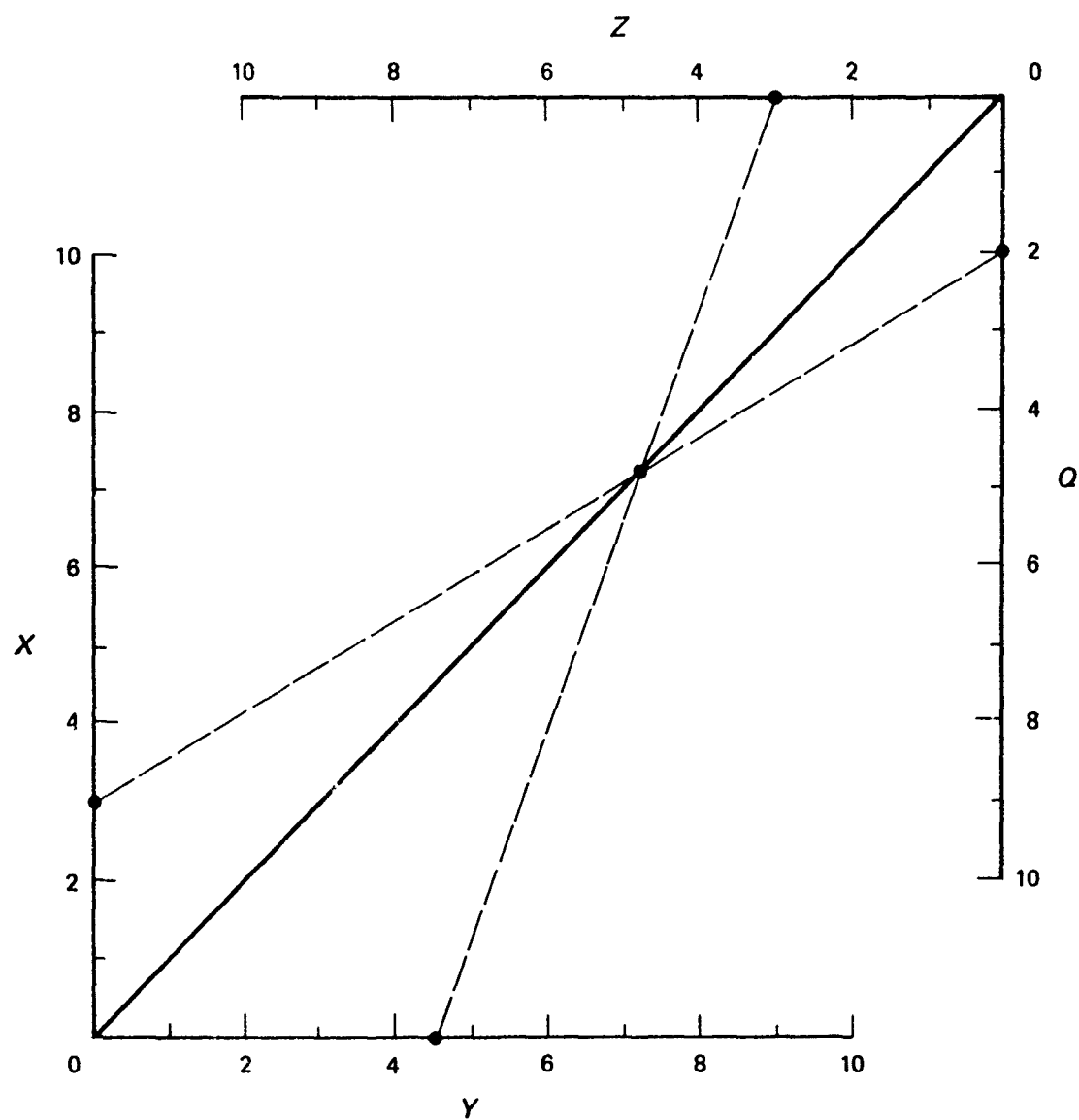
$$A = \frac{XYZ}{PQR} = \left(\left[\frac{X}{(PQ)R} \right] Y \right) Z = \frac{(2)(2)(3)}{(8)(.5)(.5)} = 6$$

FIGURE 23



$$X = \frac{YQ}{Z} = \frac{(4.5)(2)}{3} = 3$$

FIGURE 24



$$X = \frac{YQ}{Z} = \frac{(4.5)(2)}{3} = 3$$

Note: $\frac{m_X}{m_Y} = \frac{m_Q}{m_Z}$

FIGURE 25

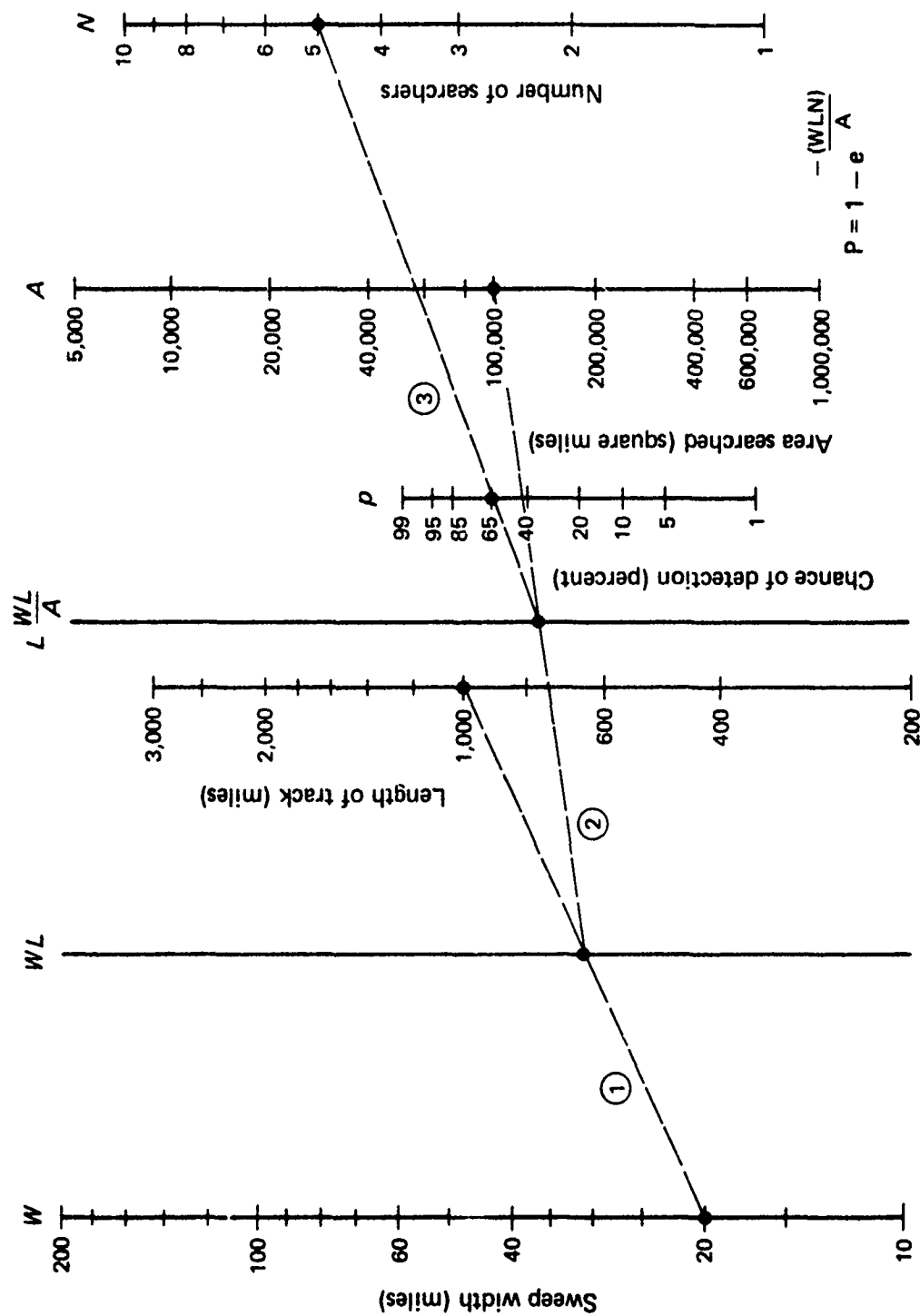
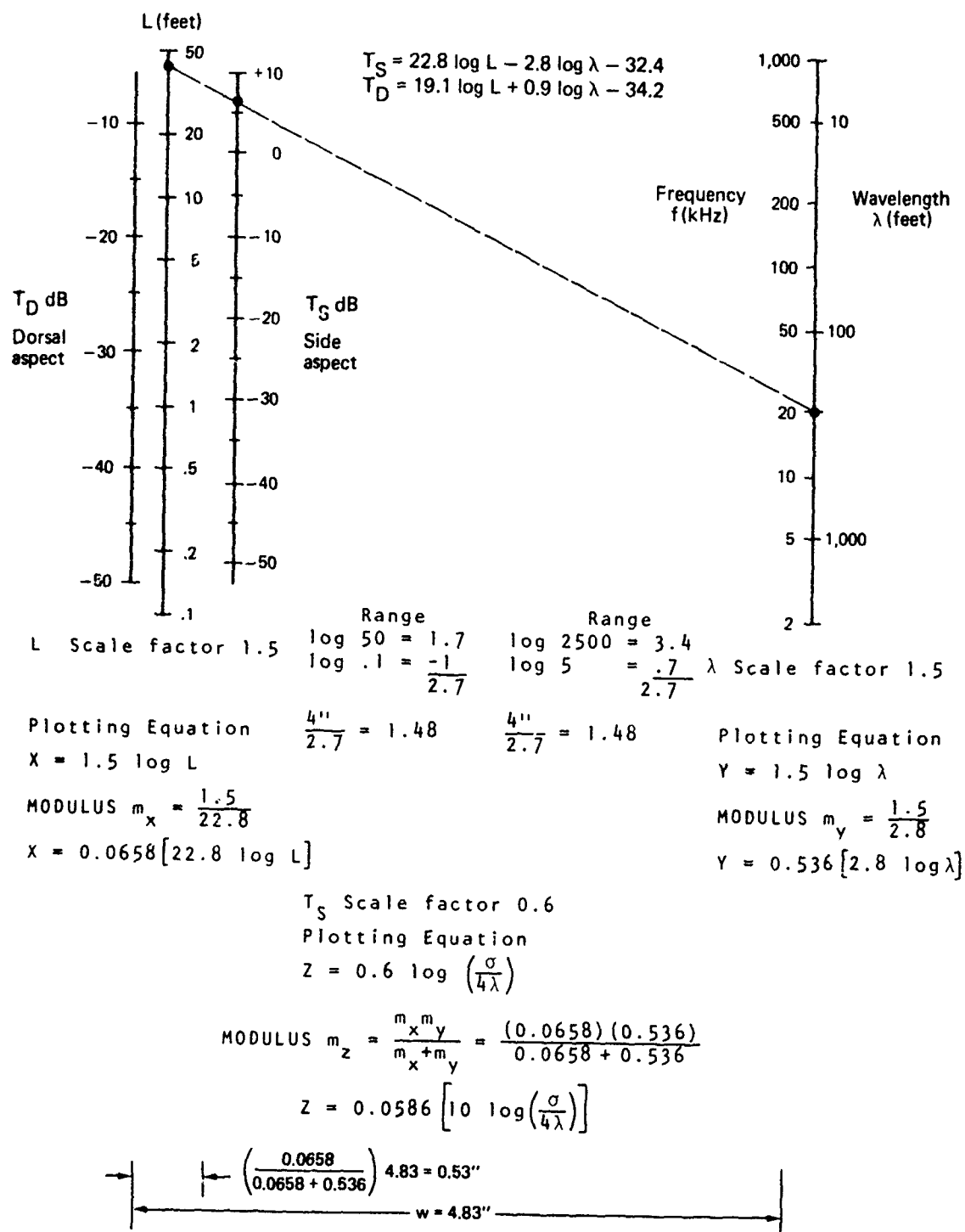


FIGURE 26

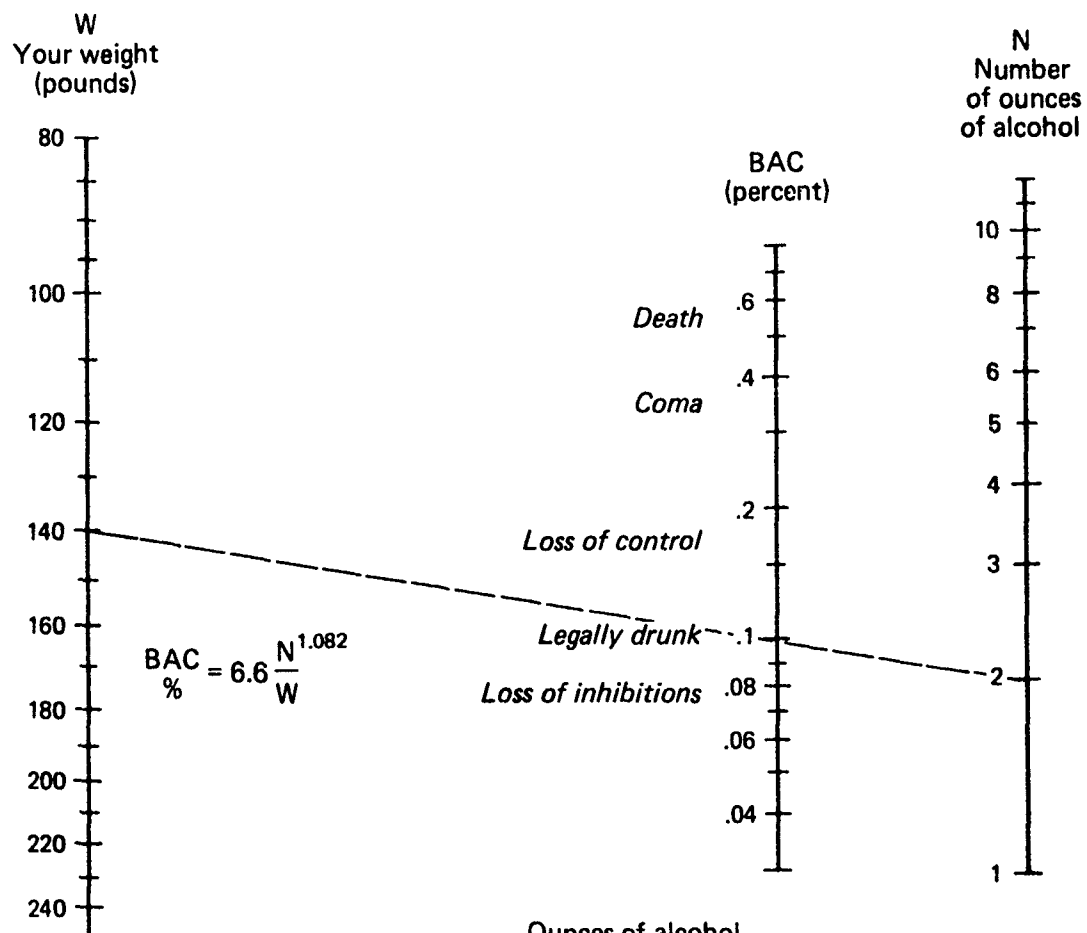
TARGET STRENGTHS OF AN INDIVIDUAL FISH*



* JASA, Vol. 49, No. 3 (Part 2), pp. 816-823, 1971.

FIGURE 27

BAR-O-GRAPH
BAC (BLOOD-ALCOHOL CONCENTRATION)
(PERCENT)



Number of drinks	Ounces of alcohol		
	Beer	Old Fash. Daiquiri	Manhattan Martini
1	.48	.6	1.05
2	.96	1.2	2.1
3	1.44	1.8	3.15
4	1.92	2.4	4.2

FIGURE 28

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